Cross-sectional scanning tunneling microscopy of InAs/GaInSb and InAsP/InAsSb superlattices for infrared applications

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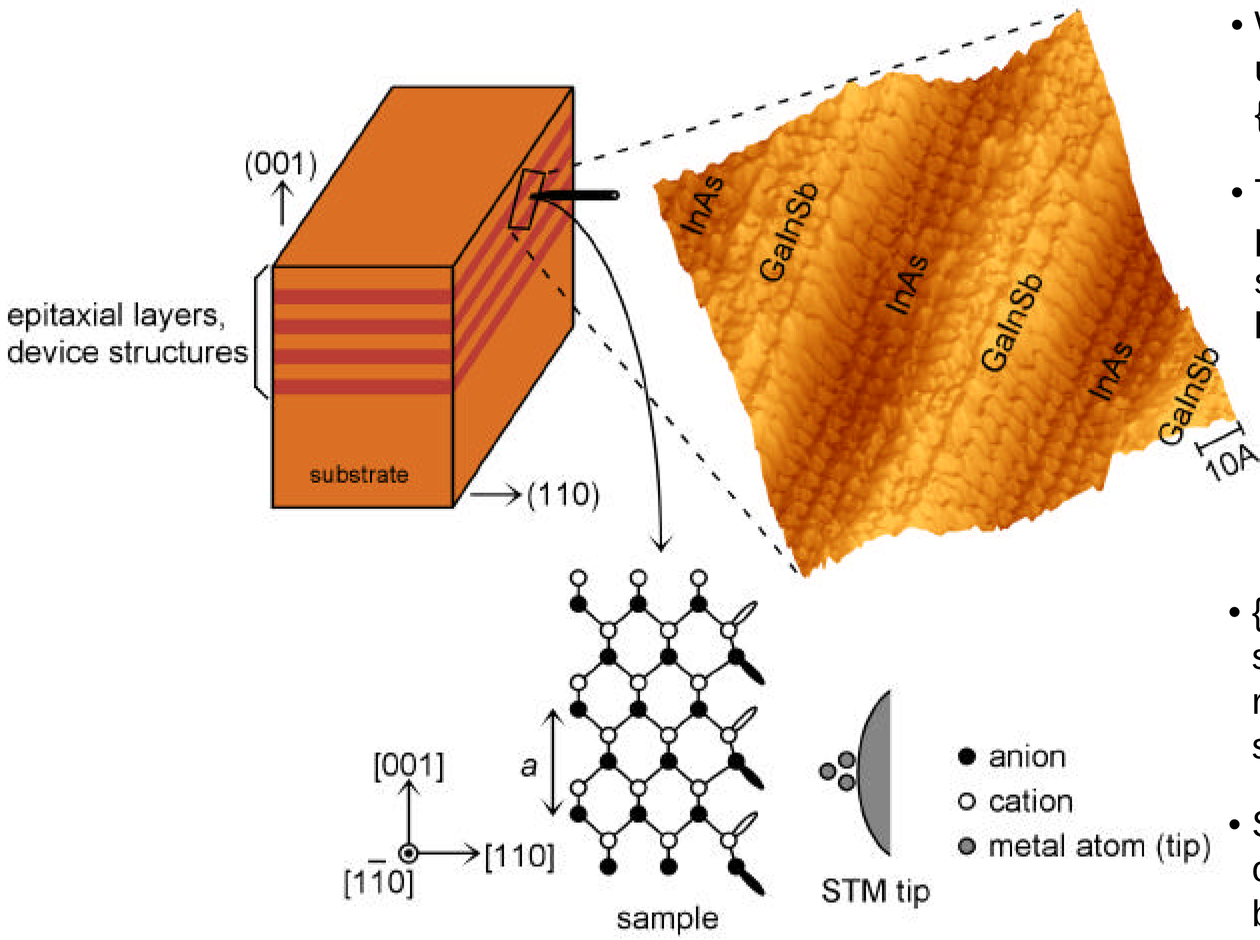
Outline

- Cross-sectional scanning tunneling microscopy
- Quantitative analysis of interface roughness in InAs/GaInSb superlattices
- Correlation of interface roughness and carrier mobility
- Compositional structure in InAsP/InAsSb superlattices
- Summary

Cross-Sectional Scanning Tunneling Microscopy



- Wafers are cleaved under ultrahigh-vacuum to expose {110} surfaces
- Tunneling measurements are performed on exposed cross-sections of epitaxial layers or devices
- {110} surfaces of III-V semiconductors generally remain 1x1; atomically flat {110} surfaces are generally unpinned
- Structure, electronic properties of epitaxial or device layers can be probed with atomic to nanometer-scale resolution

Interface Roughness in InAs/GaInSb Superlattices

• Prior work in our group demonstrated qualitative asymmetry in As/Sb interface structure:

[A. Y. Lew et al., Appl. Phys. Lett. **65**, 201 (1994); J. Vac. Sci. Technol. B **14**, 2940 (1996).]

• Cross-sectional STM enables quantitative analysis of atomic-scale interface roughness:

[R. M. Feenstra et al., Phys. Rev. Lett. **72**, 2749 (1994).]
[S. L. Skala et al., J. Vac. Sci. Technol. B **13**, 660 (1995).]
[A. Y. Lew et al., Appl. Phys. Lett. **70**, 75 (1997); Phys. Rev. B **57**, 6534 (1998).]

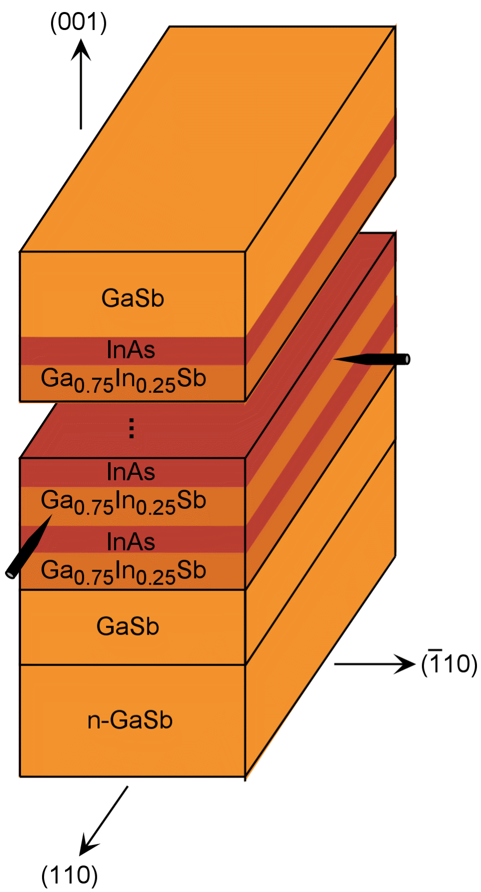
• Detailed, quantitative analysis necessary to establish correlation between atomic-scale structure probed in STM studies and “macroscopic” properties, e.g., carrier transport, in actual device structures

• STM used to quantify atomic-scale interface roughness and dependence on:

Growth sequence: InAs-on-GaInSb vs. GaInSb-on-InAs
Orientation: (110) vs. $(1\bar{1}0)$

• Quantitative measures of atomic-scale interface roughness obtained by STM compared to measurements of low-temperature carrier transport in InAs/GaInSb superlattice structures via simple modeling of interface roughness scattering

InAs/$Ga_{1-x}In_xSb$ Sample Structure and STM Geometry

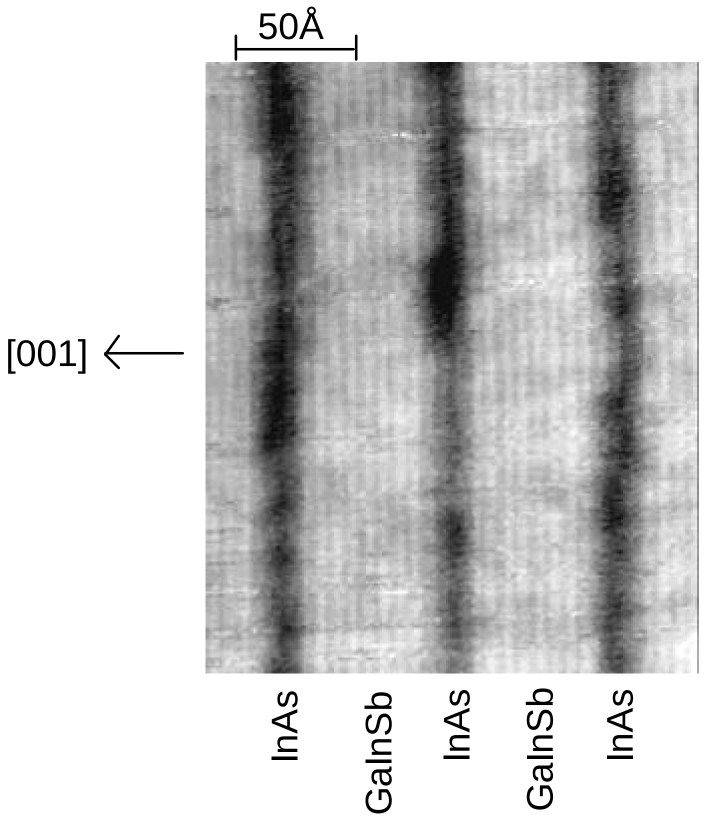


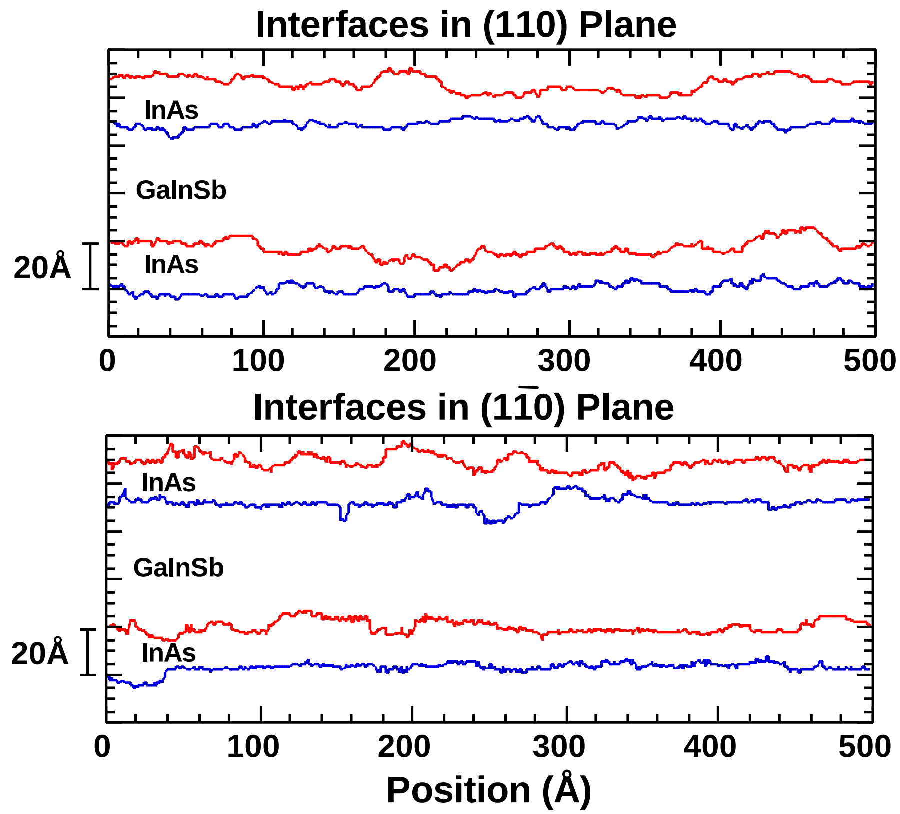
- **Superlattice structure grown by MBE at HRL Laboratories:**
  - **n-GaSb (001) substrate, 1000Å GaSb buffer layer**
  - **17Å InAs/52Å $Ga_{0.75}In_{0.25}Sb$, 150 periods**
  - **500Å GaSb cap layer**
  - **T_g = 380°C**
  - **5 s Sb soak at each interface**

- **Samples cleaved under UHV to expose either (110) or $(1\bar{1}0)$ cross-sectional planes**

- **STM characterization of both cross-sectional planes allows dependence of interface structure on orientation and growth sequence to be investigated**

Quantitative Analysis of Interface Roughness

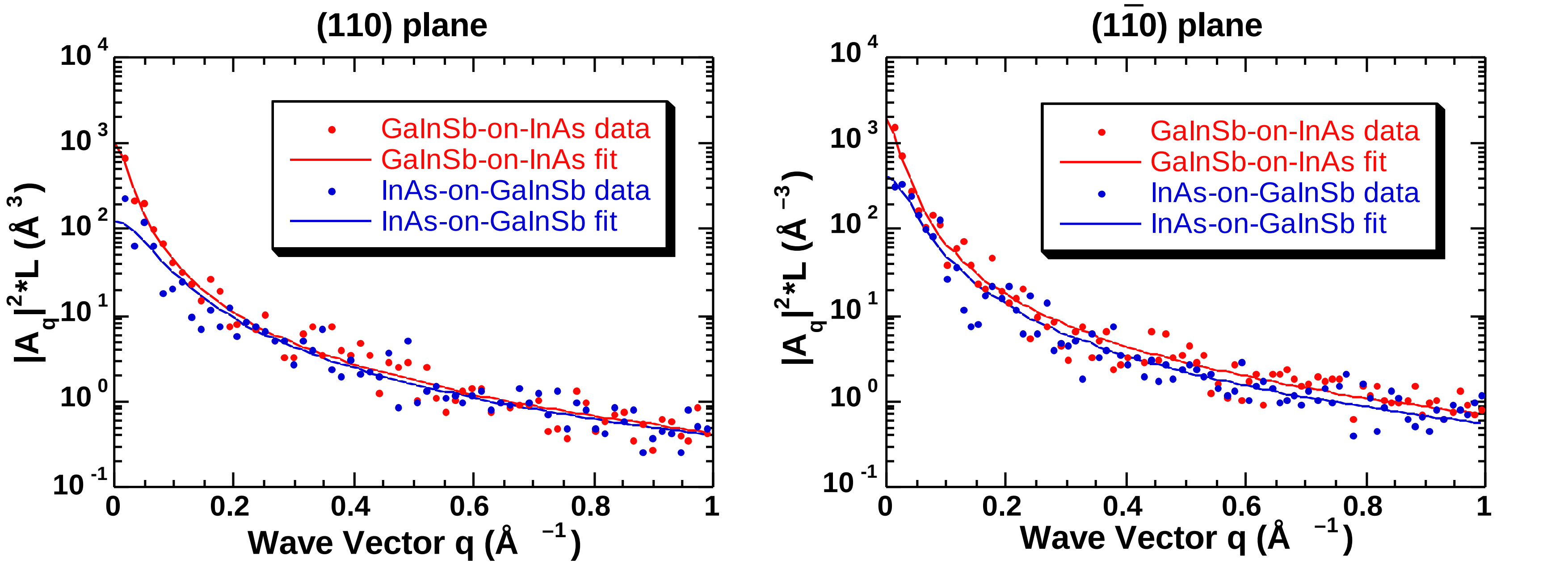




- STM imaging allows direct, quantitative investigation of atomic-scale interface structure:
  - (110) vs. (1$\bar{1}$0)
  - GaInSb-on-InAs vs. InAs-on-GaInSb
- Fourier analysis yields spectral distribution of roughness amplitude:

$$A_q = \frac{1}{N}\sum_{n=0}^{N-1} a(nd)\, e^{-iqnd} \qquad \left|A_q\right|^2 = \frac{1}{L}\cdot\frac{2\Delta^2(\Lambda/2p)}{1+q^2(\Lambda/2p)^2}$$

Spectral Distribution of Interface Roughness



GaInSb on InAs: Δ=3.2±0.2Å, Λ=301±39Å

InAs on GaInSb: Δ=1.9±0.1Å, Λ=112±16Å

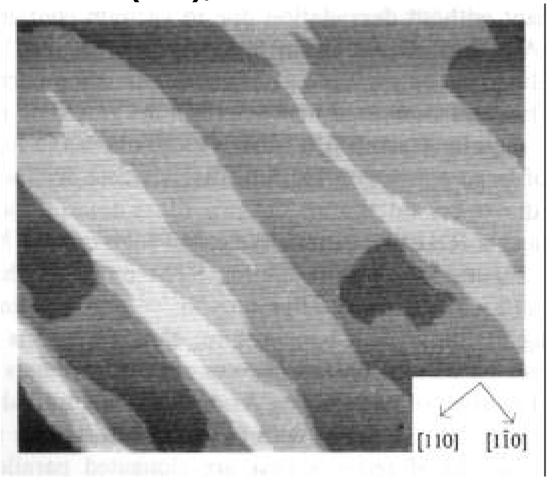
GaInSb on InAs: Δ=4.3±0.2Å, Λ=327±38Å

InAs on GaInSb: Δ=2.8±0.2Å, Λ=174±21Å

- **Interfaces rougher in (1$\bar{1}$0) plane compared to (110)**
  - *** Consistent with formation of islands elongated along [1$\bar{1}$0] during growth**
- **GaInSb-on-InAs interfaces rougher than InAs-on-GaInSb**
  - *** Consistent with laterally inhomogeneous composition at GaInSb-on-InAs interface**

Orientation Dependence of Interface Roughness

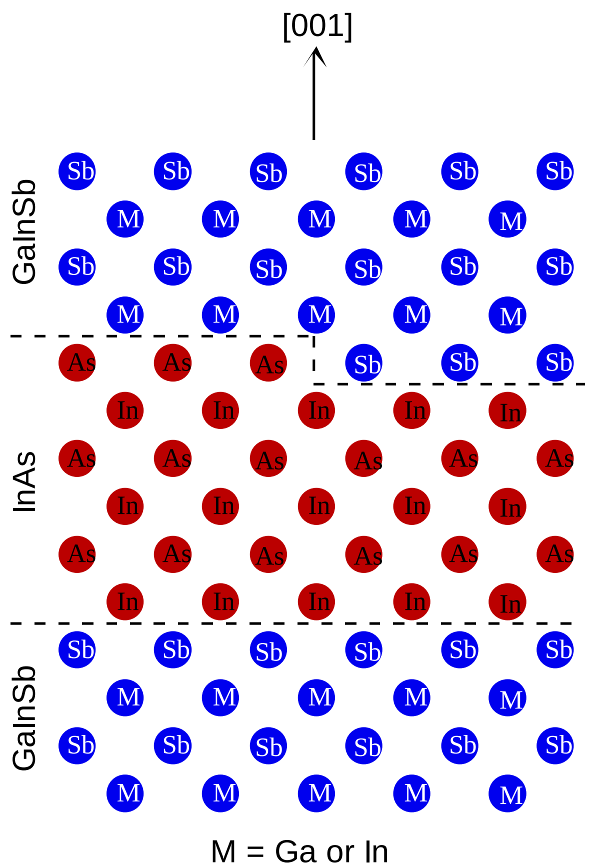
GaAs (001), 6000Åx6000Å:



[From E. J. Heller and M. G. Lagally, Appl. Phys. Lett. **60**, 2675 (1992).]

- **In MBE growth of GaAs (001), islands and terraces form elongated along the [1$\bar{1}$0] direction.**
- **Topographic features present during epitaxial growth are likely to produce roughness in heterojunction interfaces**
- **For islands and terraces running in the [1$\bar{1}$0] direction, greater interface roughness would be expected in the (1$\bar{1}$0) plane**
- **STM measurements demonstrate that interface roughness is greater in the (1$\bar{1}$0) plane than in the (110) plane, consistent with surface topography observed in growth of GaAs (001).**

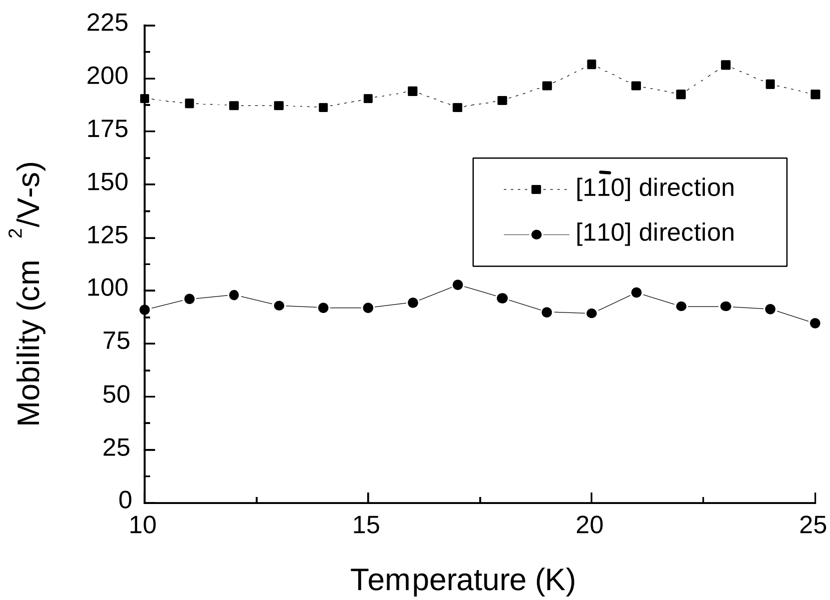
Dependence of Interface Roughness on Growth Sequence



- Prior studies have indicated that:
  InAs-on-GaInSb interface is primarily InSb-like
  GaInSb-on-InAs interface has mixed stoichiometry
- For growth of InAs on GaInSb, surface of GaInSb is already Sb-terminated
  ⇒ InSb-like stoichiometry forms naturally
- For growth of GaInSb on InAs, formation of InSb-like interface requires that As termination of InAs be converted to Sb termination
  ⇒ incomplete conversion produces mixed stoichiometry
- At interface with mixed stoichiometry, the position of the interface will vary with composition
  ⇒ increased interface roughness
- Additional interface roughness will not be present at interfaces with uniform stoichiometry

Correlation of Atomic-Scale Structure with Transport Properties

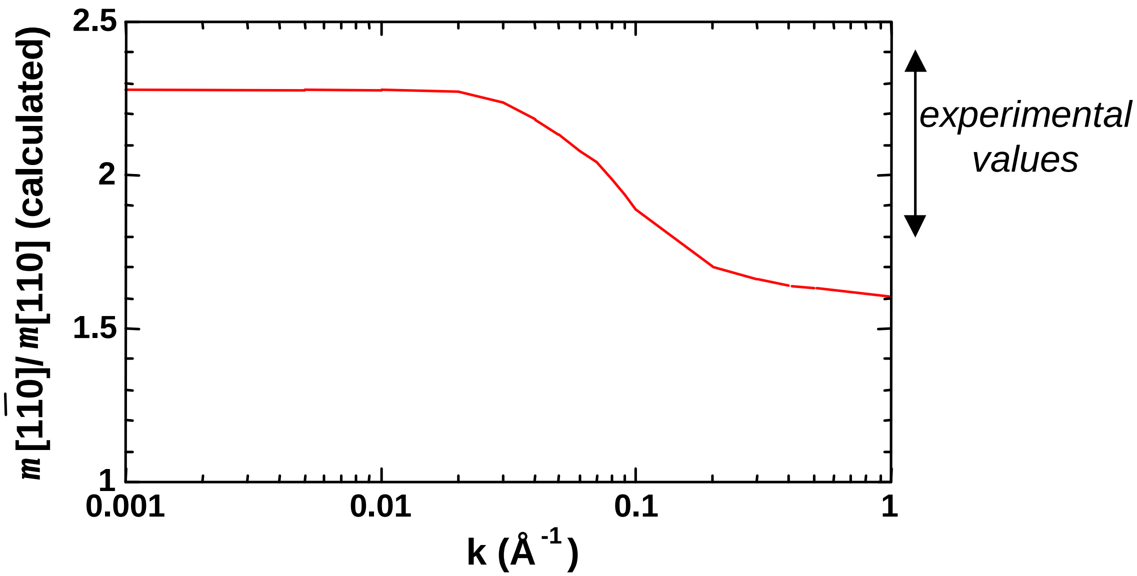
- Mobility in InAs/GaInSb superlattices has been found to be dominated at low temperatures by interface roughness scattering
- Modeling can be used to estimate quantitative effect of interface roughness anisotropy on carrier transport
- Transport measurements provide an opportunity to correlate atomic-scale morphology observed by STM with behavior of actual devices:



Transcript Modeling and Results

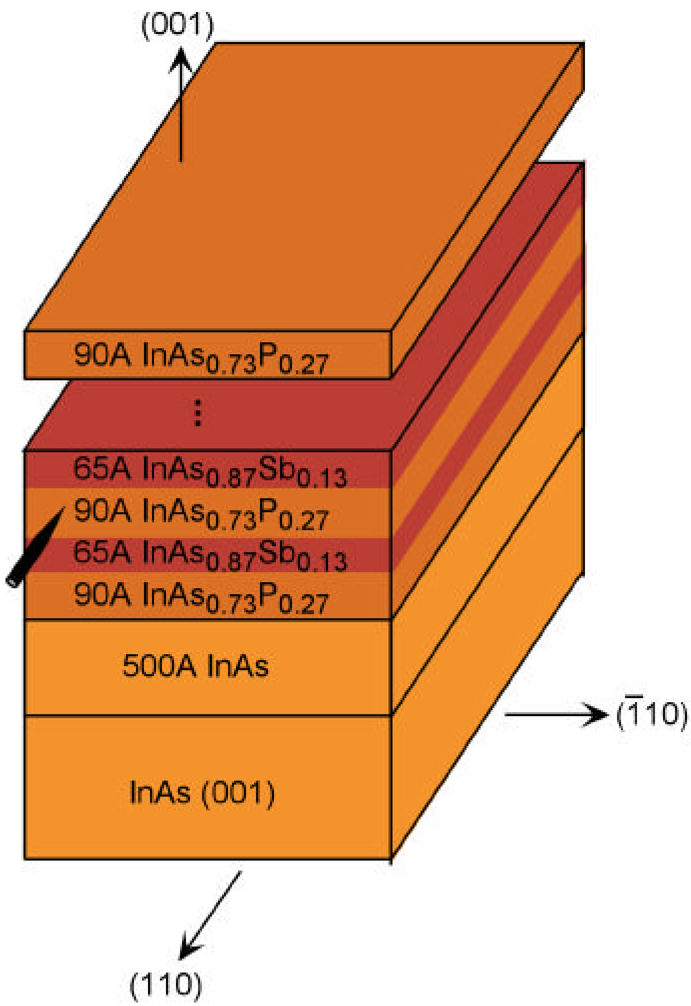
- Interface roughness data from STM used as input for estimate of scattering time:

$$\frac{1}{t(k)} = \frac{e^2 F_s^2 m^*}{2p\hbar^3} \int_0^{2p} dq\,(1-\cos q)\,S(q)\left[\frac{\Gamma(q)}{e(q)}\right]^2 \quad , \quad q = 2k\sin q/2, \;\; S(q) \sim \frac{p\Delta^2\Lambda^2}{\left[1+\left(q^2\Lambda^2/2\right)\right]^{3/2}} \longrightarrow m = \frac{e}{m^*}t$$



- Wave vectors k ≈ 0.01-0.1Å^{-1} are most relevant for transport measurements
- Experimentally observed mobility anisotropy ratios for superlattices grown on GaSb (001) are ~1.8-2.4, in semiquantitative agreement with simple model
- Need to incorporate detailed superlattice band structure effects into modeling of transport

$InAs_{1-x}P_x/InAs_{1-y}Sb_y$ Heterostructures



- **Sample grown by MOCVD at Sandia:**
  90Å $InAs_{0.73}P_{0.27}$/65Å $InAs_{0.87}Sb_{0.13}$
  10-period superlattice
  InAs (001) substrate

- **Similar superlattice structures used for fabrication of infrared LED's, lasers operating at 3.2-4.4mm**
  [S. R. Kurtz et al., *Appl. Phys. Lett.* **70**, 3188 (1997).]
  [R. M. Biefeld et al., *J. Elec. Mater.* **26**, 1225 (1997).]

- **Ordering, compositional clustering within superlattice alloy layers can influence band gaps, linewidths etc.**

$InAs_{1-x}P_x/InAs_{1-y}Sb_y$ Heterostructures

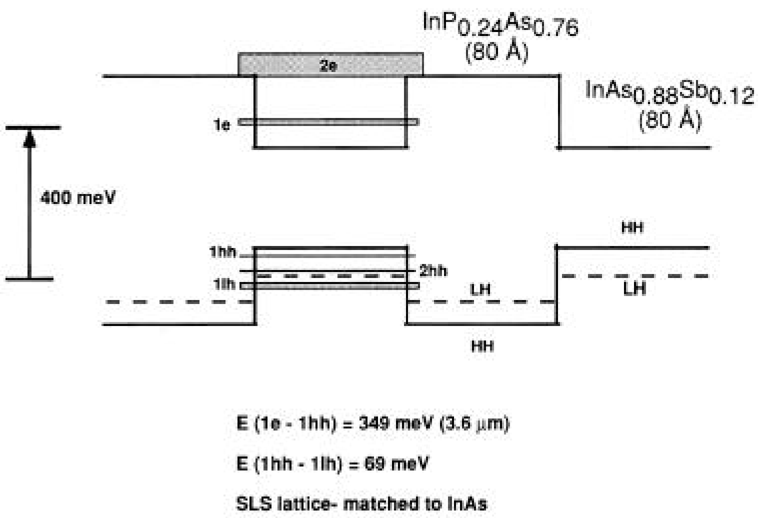
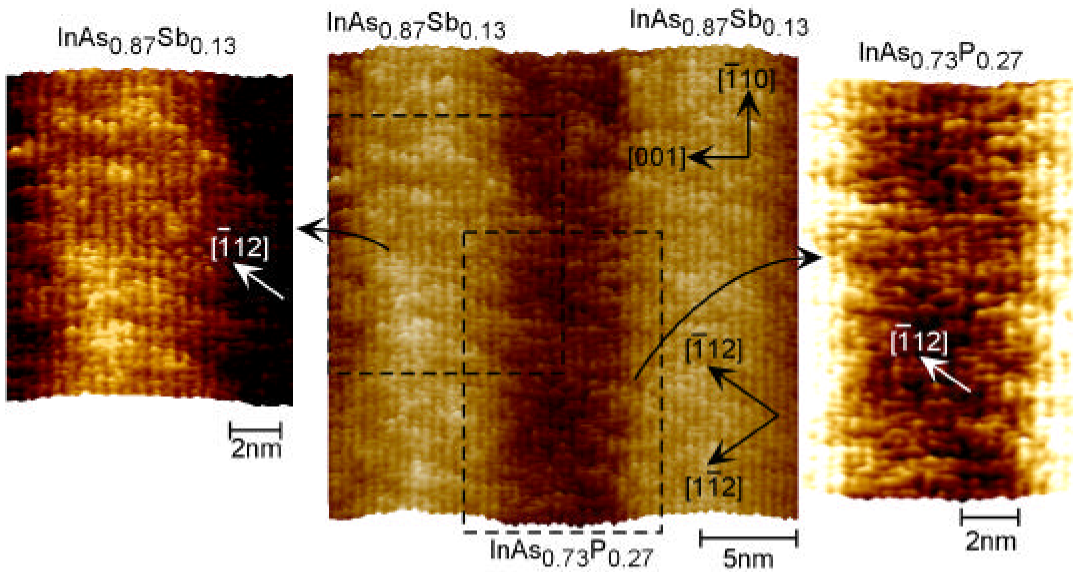


FIG. 1. Band alignments and quantum confinement state energies (drawn to scale) for an $InAs_{0.88}Sb_{0.12}/InAs_{0.76}P_{0.24}$ (80 Å/80 Å) SLS.

[From S. R. Kurtz et al., *Appl. Phys. Lett.* **70**, 3188 (1997).]

- **Quantum-well optical properties will be highly dependent on structure of $InAs_{1-x}P_x$ and $InAs_{1-y}Sb_y$ alloy layers and of heterojunction interfaces**
- **Ordering could lead to reduction in bulk alloy energy band gaps**
- **Compositional clustering, interface roughness would lead to energy shifts, linewidth broadening**
- **Band alignment is such that:**
  - **$InAs_{1-y}Sb_y$ layer will appear higher in constant-current topographic image**
  - **As-rich regions in $InAs_{1-x}P_x$ and Sb-rich regions in $InAs_{1-y}Sb_y$ will appear higher in topographic image**

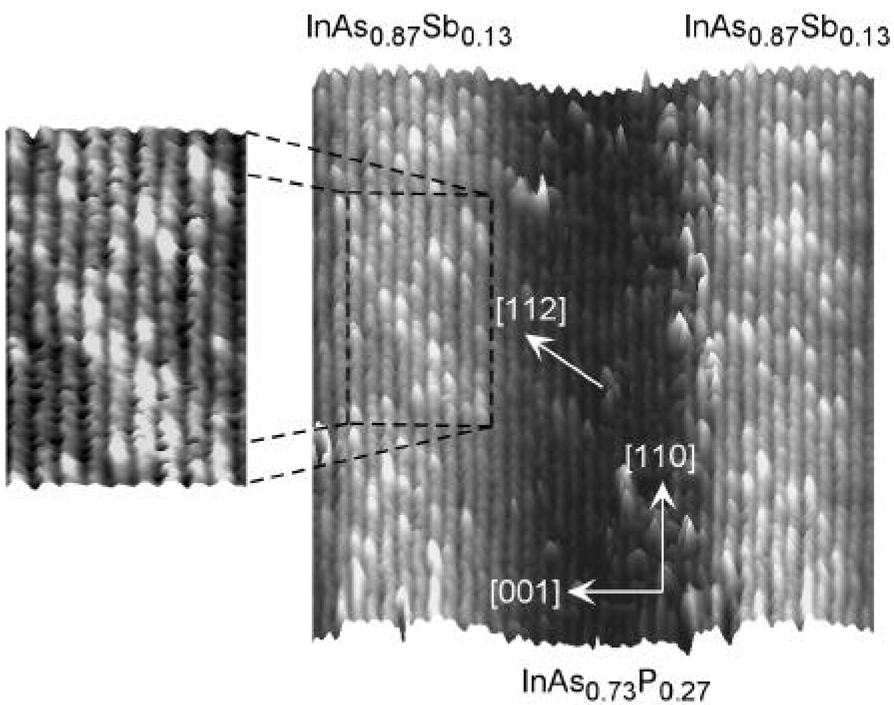
(110) Cross-Sectional Imaging of $InAs_{1-x}P_x/InAs_{1-y}Sb_y$ Structure



- Significant compositional inhomogeneity (clustering) observed in both $InAs_{1-x}P_x$ and $InAs_{1-y}Sb_y$
- P-rich regions (dark) in $InAs_{1-x}P_x$ layer appear preferentially aligned along $[\bar{1}12]$ direction
- Sb-rich clusters (bright) observed in $InAs_{1-y}Sb_y$ layer, no clear preferential orientation
- Cross-incorporation of Sb into $InAs_{1-x}P_x$ or P into $InAs_{1-y}Sb_y$ difficult to determine unambiguously
- Previously reported TEM studies showed partial ordering in $InAs_{1-y}Sb_y$ alloys with variations in relative strength of ordering along $[\bar{1}11]$, $[1\bar{1}1]$ directions

[D. M. Follstaedt et al., *J. Elec. Mater.* **24**, 819 (1995).]

$(\bar{1}10)$ Cross-Sectional Imaging of $InAs_{1-x}P_x/InAs_{1-y}Sb_y$ Structure



- **Compositional fluctuations clearly visible in InAsSb layer**
- **Evidence of preferential orientation?**

Summary

- Cross-sectional STM provides atomic-scale information about heterojunction interface and alloy layer structure

- Quantitative analysis of InAs/GaInSb interface roughness reveals influence of stoichiometry, surface structure during growth on final interface structure

- Quantitative correlation established between interface roughness and carrier transport properties

- Preliminary studies of InAsP/InAsSb superlattices provide insight into nanoscale compositional structure of alloys